Overview of Nanofibers Applications for Air Cleaning

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Outline

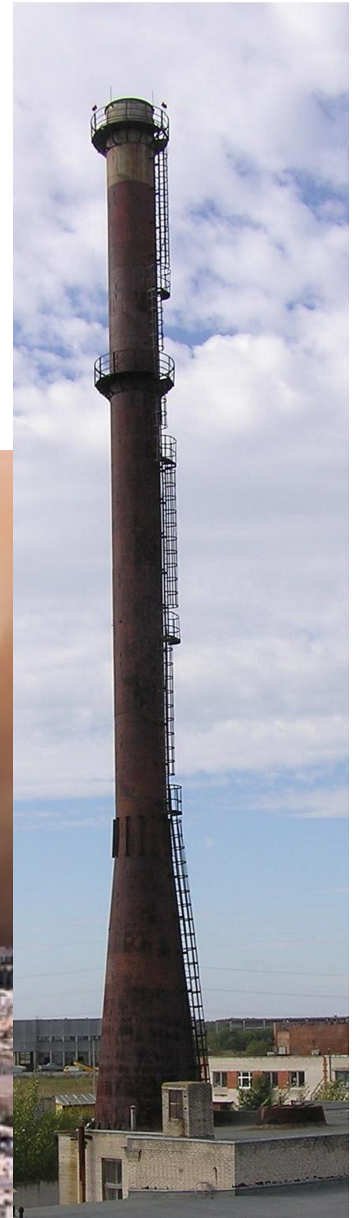
- The need for air cleaning.
- Theoretical and empirical approach to air filtration.
- Major parameters of the filtration process, the role of fiber diameter and air velocity. Dust cake formation, filter lifetime.
- Filter media classification - benefits of using nanofiber filter media.
- Customer expectations. Design trends.
- Selected applications of nanofiber filter media:
  - Motor vehicle filtration,
  - Gas turbine filtration – self-cleaning filtration,
  - Heating and ventilation,
  - Clean room applications,
  - Personal protection.
- Filter media trend, total filtration system development.
- Conclusions.

The Need for Air Cleaning

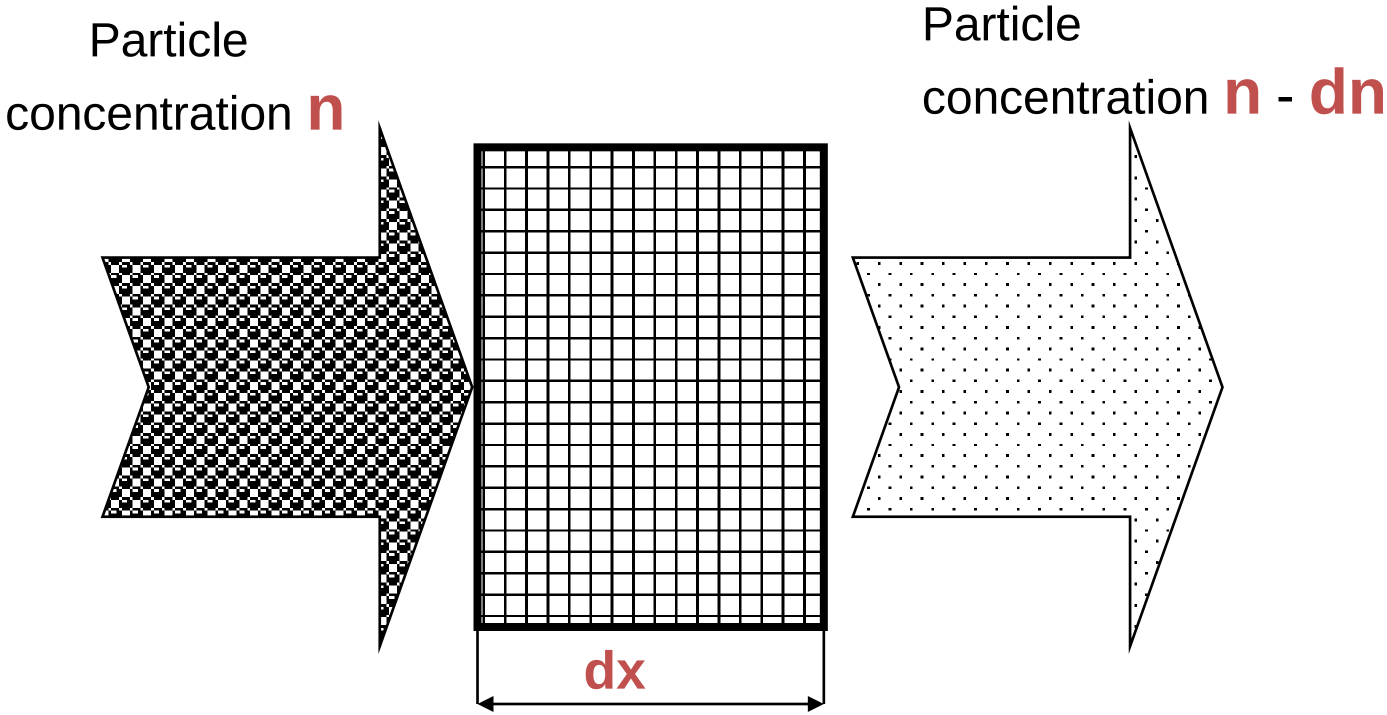
- **Air filtration intake systems perform these functions:**
  - Transport air
  - Filter air
  - Reduce intake noise
  - Remove moisture
- **Provide clean air for machine components**
- **Provide clean air for cabin, building occupants.**
- **Provide protection to people operating in hazardous environments (military, mining, firefighting, etc) - personal protection.**
- **Clean air is needed to:**
  - Prevent wear of moving parts within engines, gas turbines, compressors, blowers, etc.
  - Prevent workers in high dust environments from developing respiratory problems.
  - Provide controlled environment in "clean room" applications.

All of air contaminants entering equipment can and will lead to unnecessary wear, shorter machine life, and increased maintenance costs.

Environment



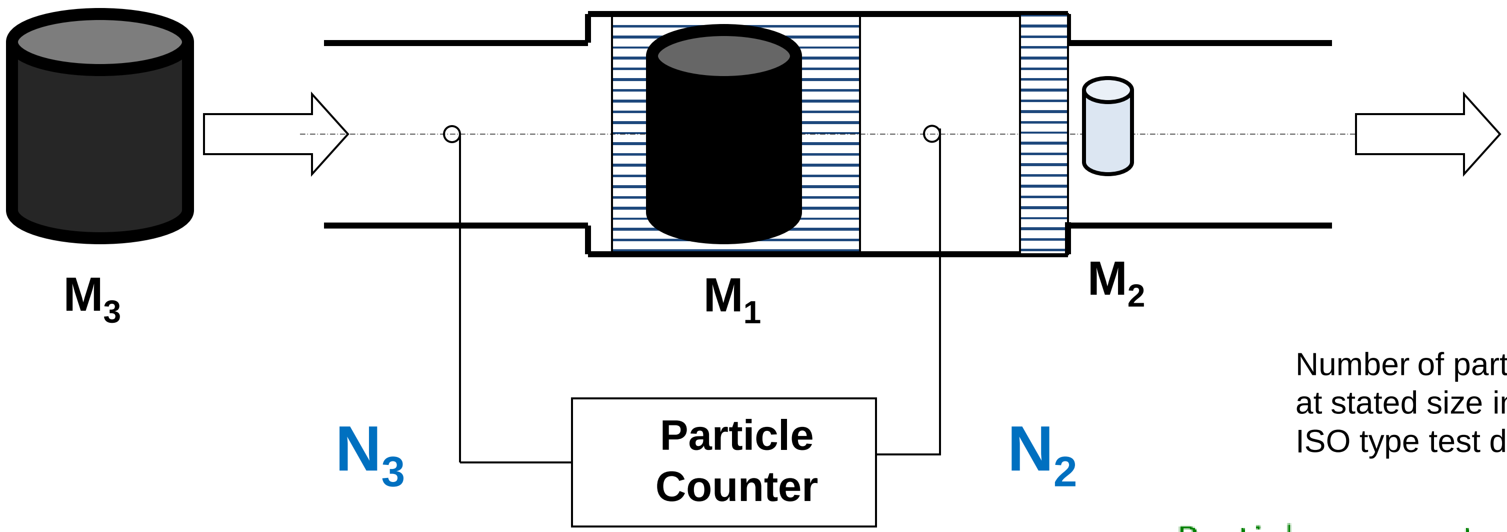
Filter Modeling - General Approach



$$n = n_0 e^{-kx}$$

Constant k describes media properties (material, porosity, thickness, fiber diameter, etc in media of thickness = x).

Experimental Methods



Number of particles at stated size in 1g of ISO type test dust

Particle concentration:

d=1 μm	⇔ $1.8x10^9$
d=2 μm	⇔ $3.8x10^8$
d=3 μm	⇔ $1.1x10^8$
d=4 μm	⇔ $5.6x10^7$
d=5 μm	⇔ $3.0x10^7$
d=10 μm	⇔ $4.2x10^6$
d=20 μm	⇔ $5.7x10^5$
d=40 μm	⇔ $5.8x10^4$
d=80 μm	⇔ $9.6x10^2$

Gravimetric - weight (mass) of polydisperse challenge contaminant or concentration of monodisperse contaminant.

Fractional - number of particles at stated size.

$$E_G = 1 - \frac{M_2}{M_3} \times 100$$

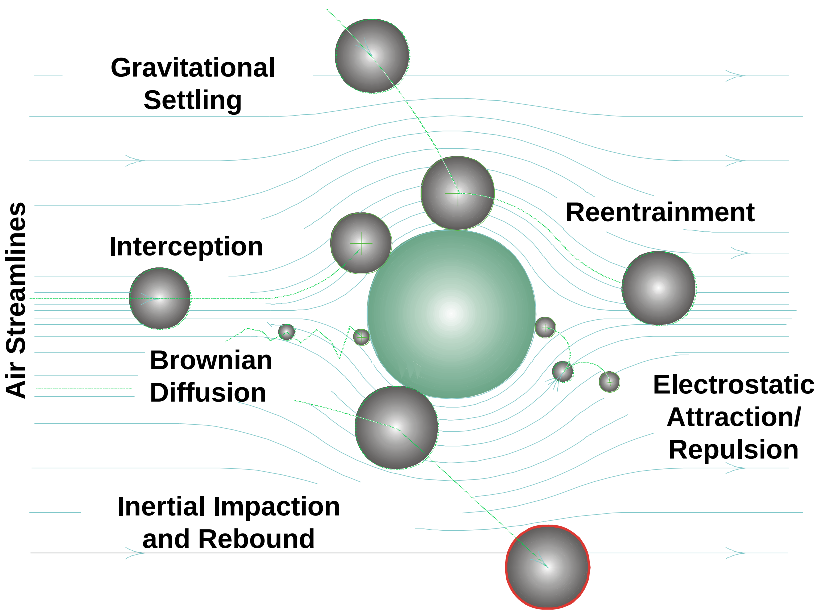
$$E_G = \frac{M_1}{M_1 + M_2} \times 100$$

E = 1 - P

Mechanics of Collection

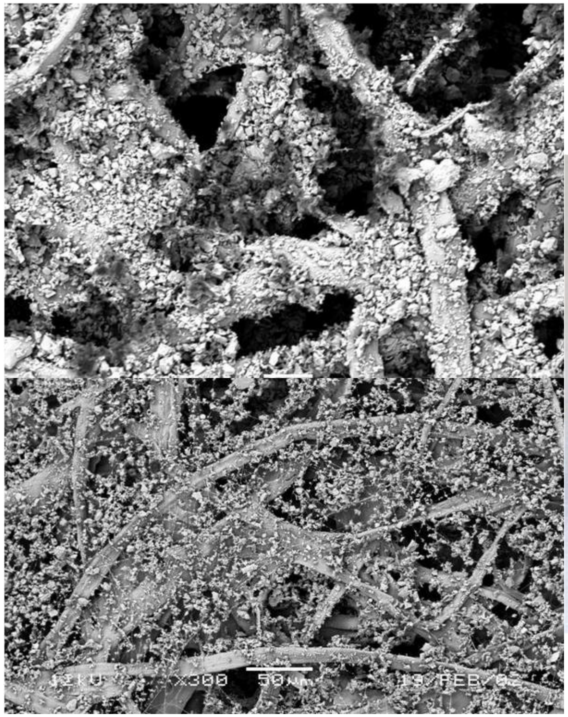
The basis of predicting the collection efficiency of a filter medium is the collection efficiency of a single fiber. The most important independent variables are:

Fiber



- **Fiber diameter**
- **internal filter air velocity**
- **Particle diameter**
- **Electrical charge**

Media



- **Fiber diameter**
- **Thickness**
- **Air face velocity**
- **Solidity (packing density)**
- **Particle diameter**
- **Dust cake porosity**

Filter

- **Area**
- **Flow rate**
- **Filter ID, OD, Length**

Mathematical Models

The purpose of modeling in filtration is:

- To understand physical process of filtration
- To understand the role of every variable.
- **To predict filter performance.**
- To improve filter design.

Analytical

based on known physical laws expressed in algebraic or differential equations and solved mathematically.

Empirical

simple mathematical expressions are used to fit experimental results - e.g., regression.

FILTER DESIGN

Statistical

models similar to empirical; however, experimental results used to fit into a predominated statistical concept.

Numerical

based on physical laws and solved using numerical methods.

A general agreement between experiment and filtration theory is an indication of test suitability. If there is no agreement, the theory, experiment, or both are faulty.

Combined Mechanisms

$$E = E_D + E_R + E_{DR} + E_{ST}$$

- Since the overall efficiency is a combination of the efficiencies of all filtration mechanisms, a minimum occurs at a particle size of 0.1 to 0.5 µm, depending on aerosol velocity. The minimum decreases and it is shifted toward smaller particle diameters with increasing velocity. It is shifted toward larger particles with increasing fiber diameter.
- Efficiency increases rapidly with decreasing fiber diameter. For instance: using 50 μm fibers instead of 1 μm leads to a decrease in filter efficiency by a factor of 2000 – therefore, nanofiber media with 0.1-0.4 μm fibers have much higher efficiency than other media made of cellulose fibers having 20 μm fibers. A general rule for fiber diameter selection is that the diameter should be equal to or no more than three times the diameter of the particle diameter to be removed from the air stream. This results in close to 100% efficiency for particles smaller than 10 μm; however, where particles have significant momentum, they can bounce off fibers, decreasing filter efficiency for more open media.

Basic Filtration Performance

Filtration theory shows that fiber diameter is the fundamental filter parameter. All other parameter can be varied.

Efficiency

$$E = 1 - \exp\left\{-\frac{2\alpha \cdot x}{(1-\alpha)\pi \cdot R}\right\} \cdot \eta$$

$$\eta = f(v, R, r, \alpha)$$

Where,

E = Filter Efficiency

$\left\{-\frac{2\alpha \cdot x}{(1-\alpha)\pi \cdot R}\right\}$ = Length of fibers

η = Single fiber efficiency

v = Air velocity inside the filters

α = Volume fraction of fibers

x = Filter thickness

R = Fiber radius

r = Particle radius

Pressure Drop

$$\Delta P = \frac{\alpha \cdot x \cdot A}{\pi \cdot R^2} \cdot \mu \cdot v \cdot f(\alpha)$$

Where:

ΔP = Pressure drop

$\frac{\alpha \cdot x \cdot A}{\pi \cdot R^2}$ = Length of fibers

$\mu \cdot v \cdot f(\alpha)$ = Fiber drag

v = Air velocity

α = Volume fraction of fibers

x = Filter thickness

R = Fiber radius

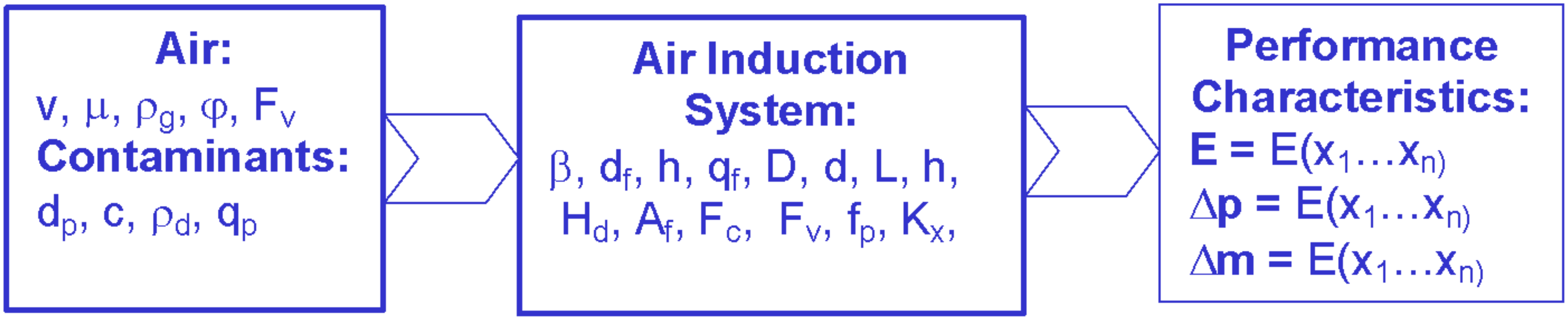
μ = Viscosity

$f(\alpha)$ = function of α

General equation $\boxed{\Delta P = k_1 v + k_2 v^2}$

$$\Delta p_m = \frac{\mu \cdot v_a \cdot h}{d_f^2 / 4}\left[16 \cdot \alpha^{1.5}\left(1 + 56\alpha^3\right)\right]$$

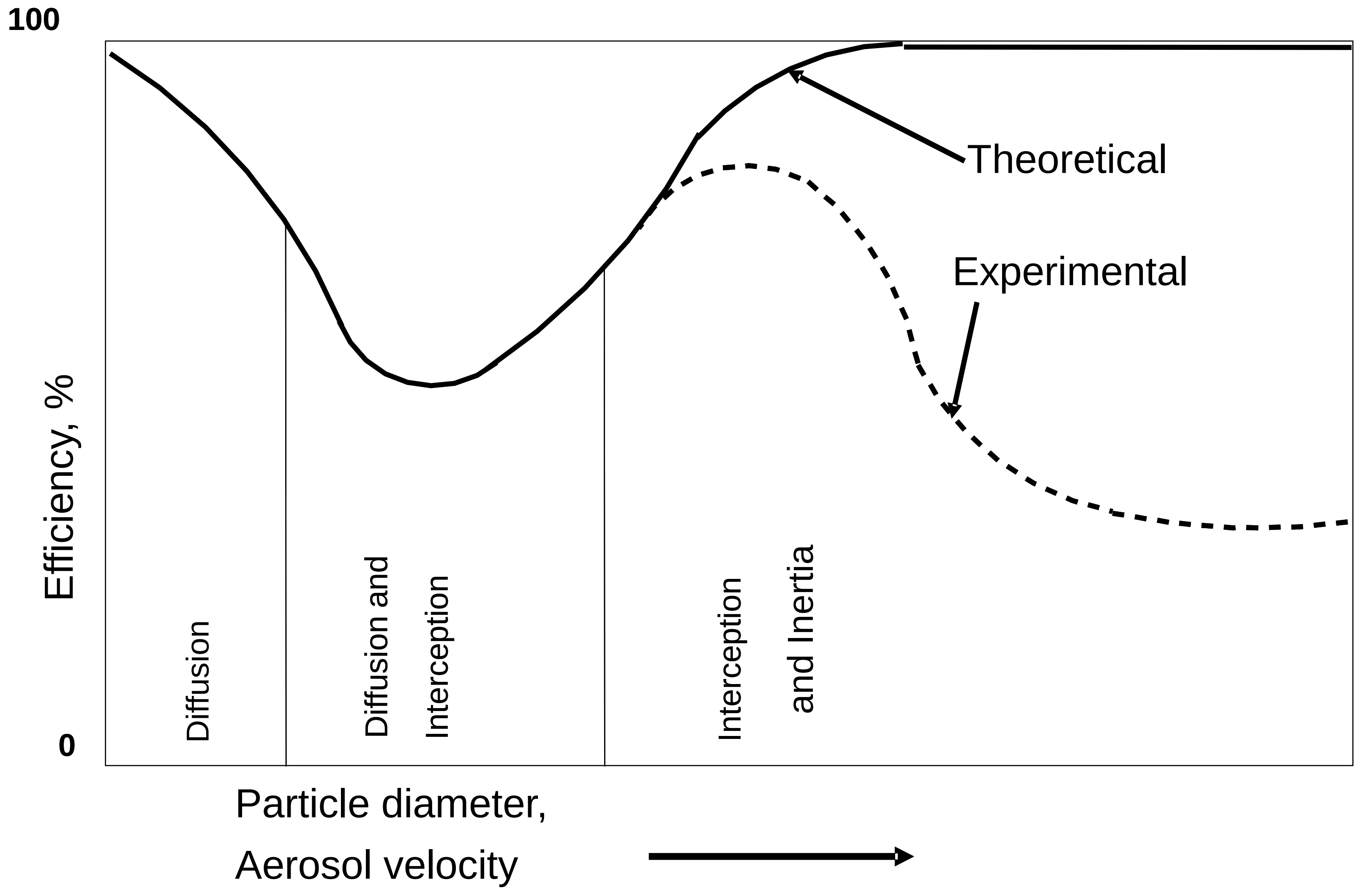
Major Parameters of Filtration Process



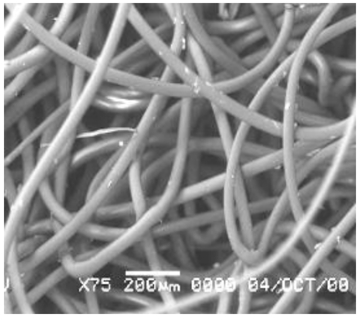
$$E, \Delta P, \Delta M = f\,(v, d_f, d_p, h, \beta, \rho_g, A_f, \rho_d, c, \mu, \varphi, q_p, q_f, f_p, F_v, P_l, F_c, H_d, K_x \ldots)$$

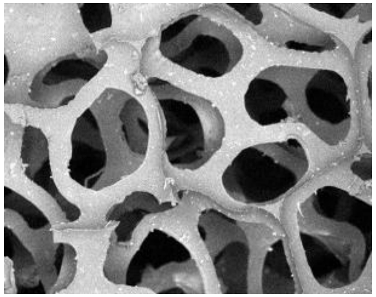
E = efficiency, ΔP = pressure drop, ΔM = dust holding capacity.
v = aerosol velocity, h = media thickness, d_f = fiber diameter, d_p = particle diameter, β = packing density (solidity), ρ_g = air density, A_f = surface area, ρ_d = dust density, c = dust concentration, μ = air viscosity, φ = humidity, q_p = dust electrical charge, q_f = fiber electrical charge, f_p= filter vibration, F_v= flow pulsation, P_l=pleat configuration, F_c=filter configuration, H_d=housing design, and K_x = coefficient.

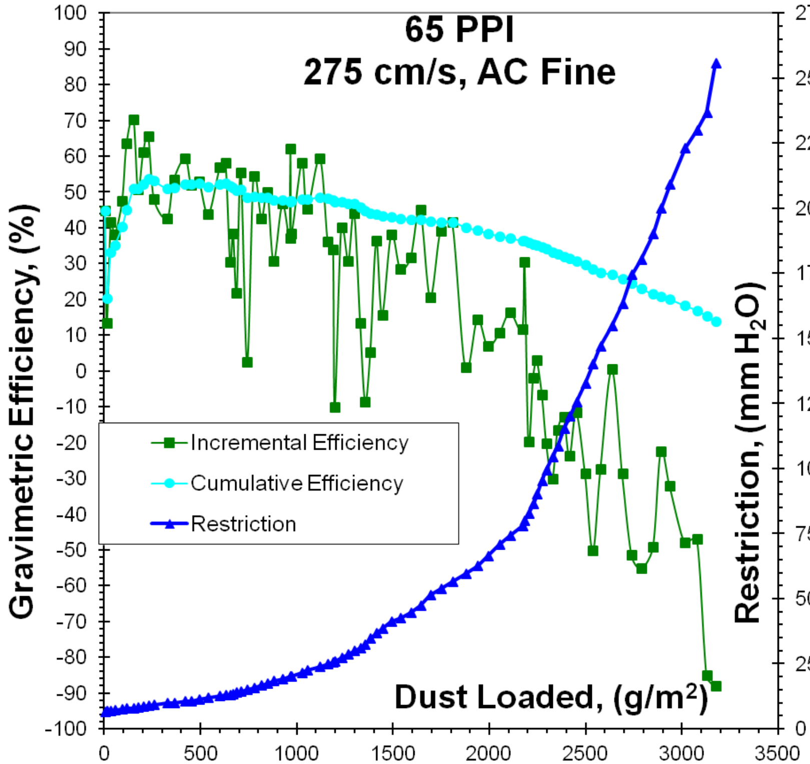
Minimum Efficiency

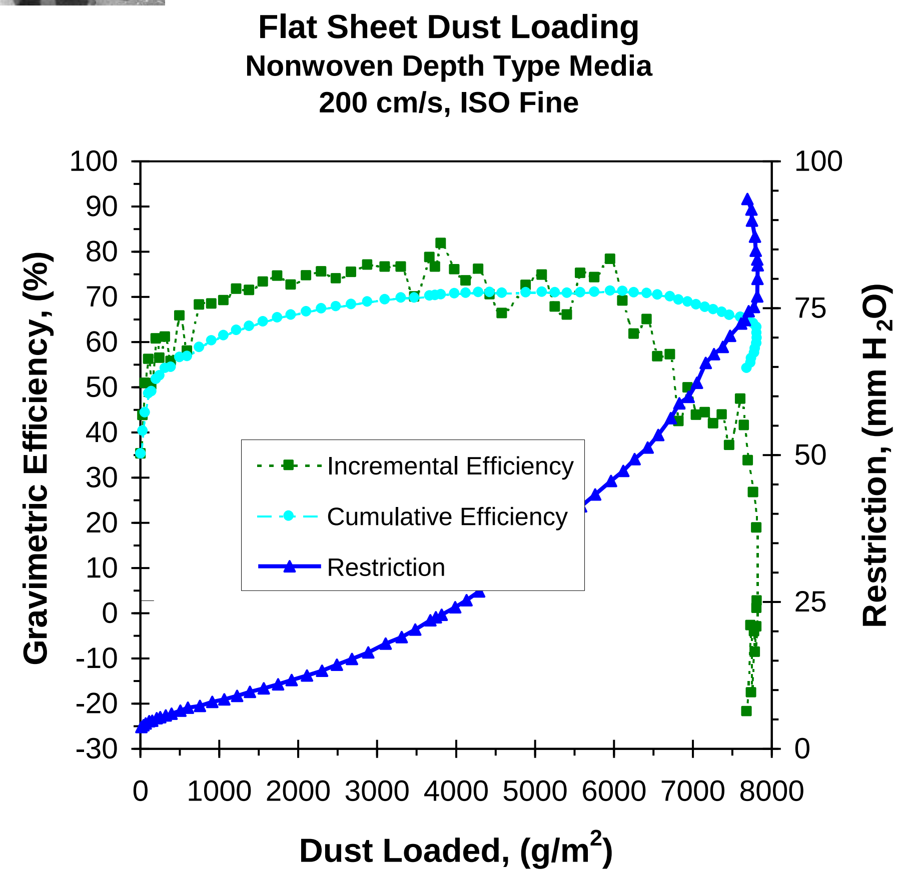


Prefilter Performance Characteristics

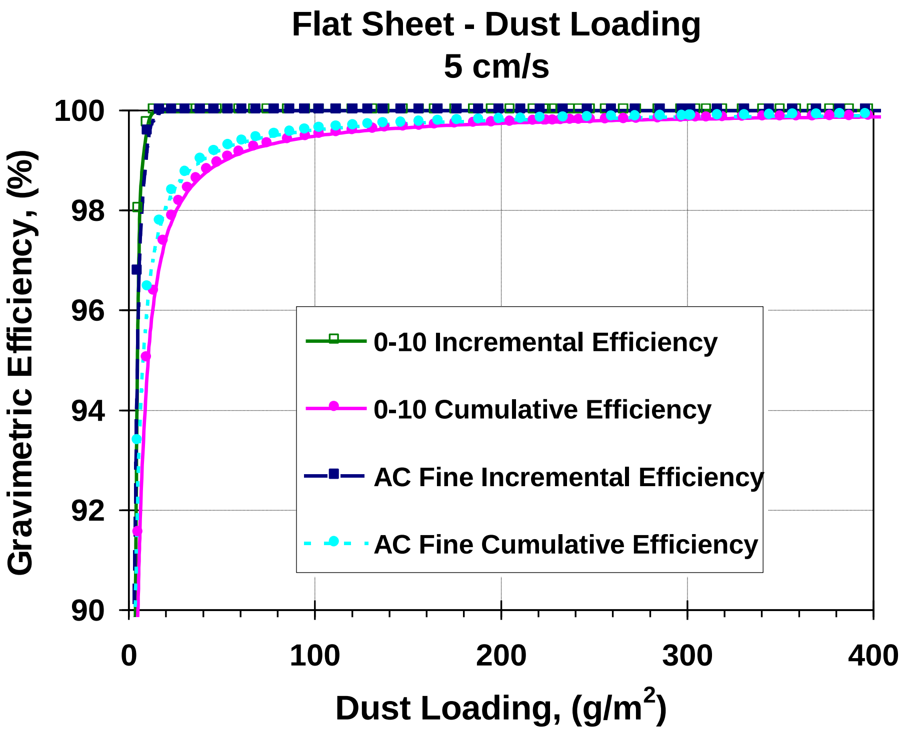


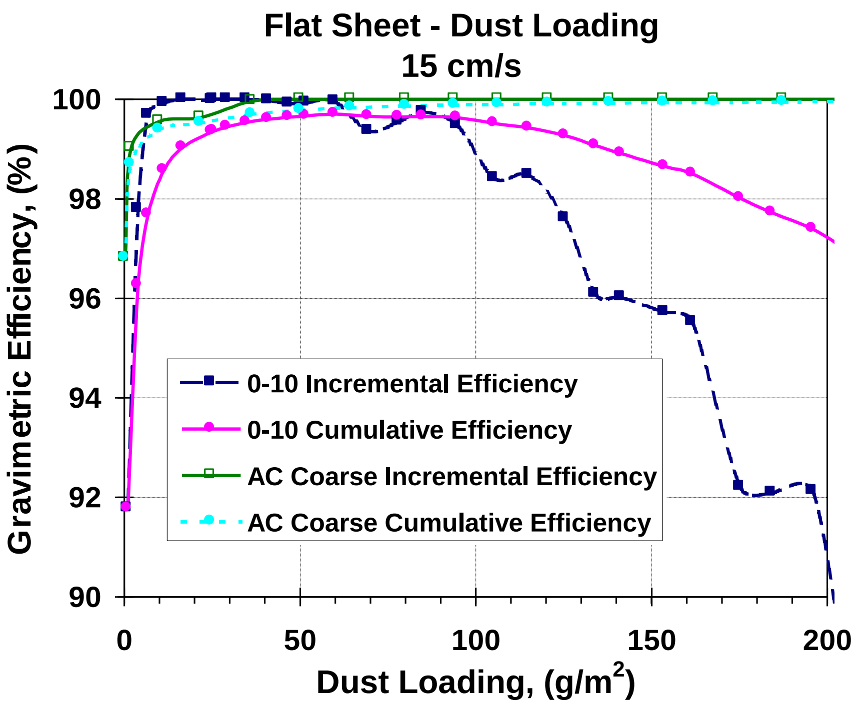






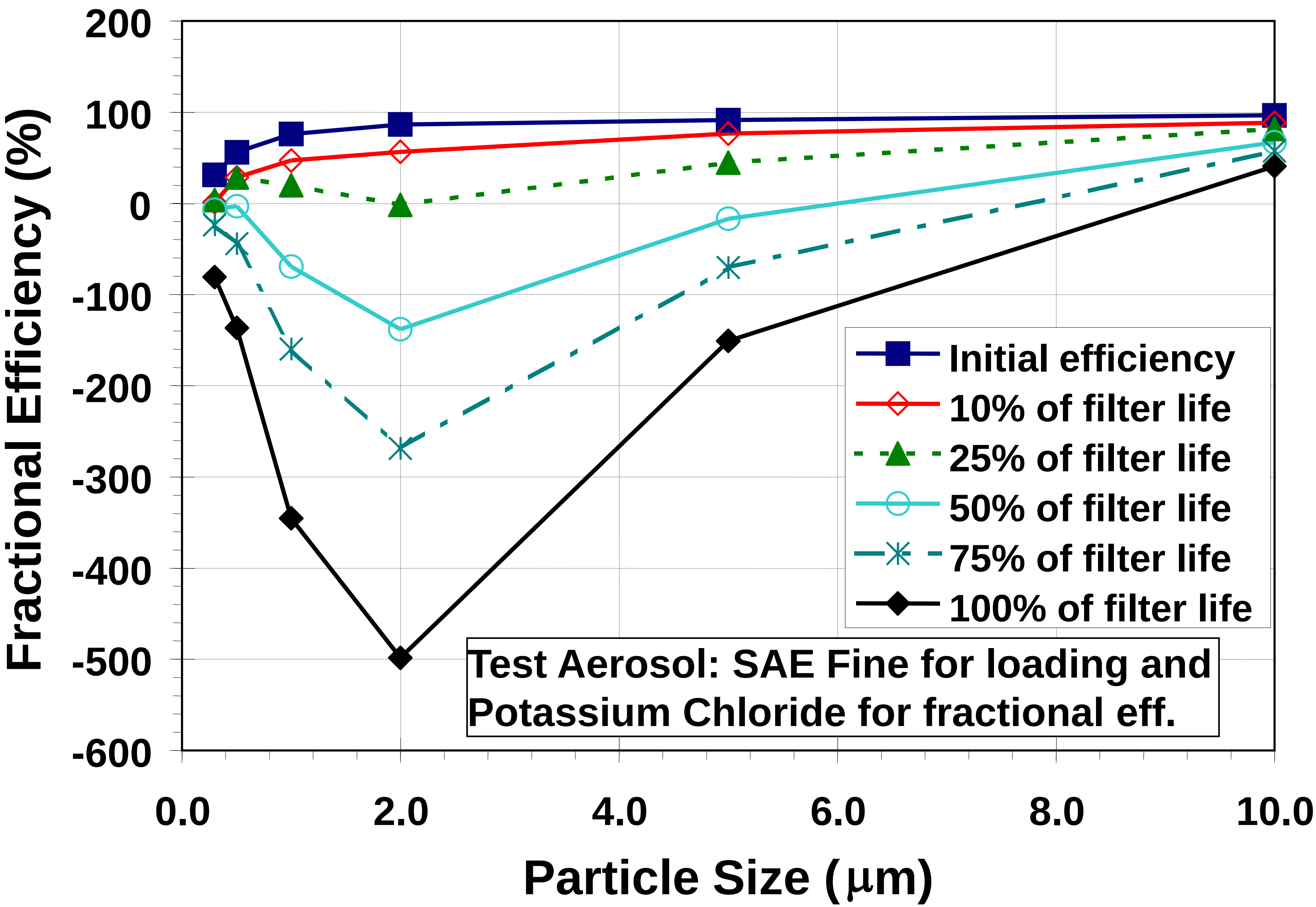
Cellulose filter media performance at 5 cm/s and 15cm/s.



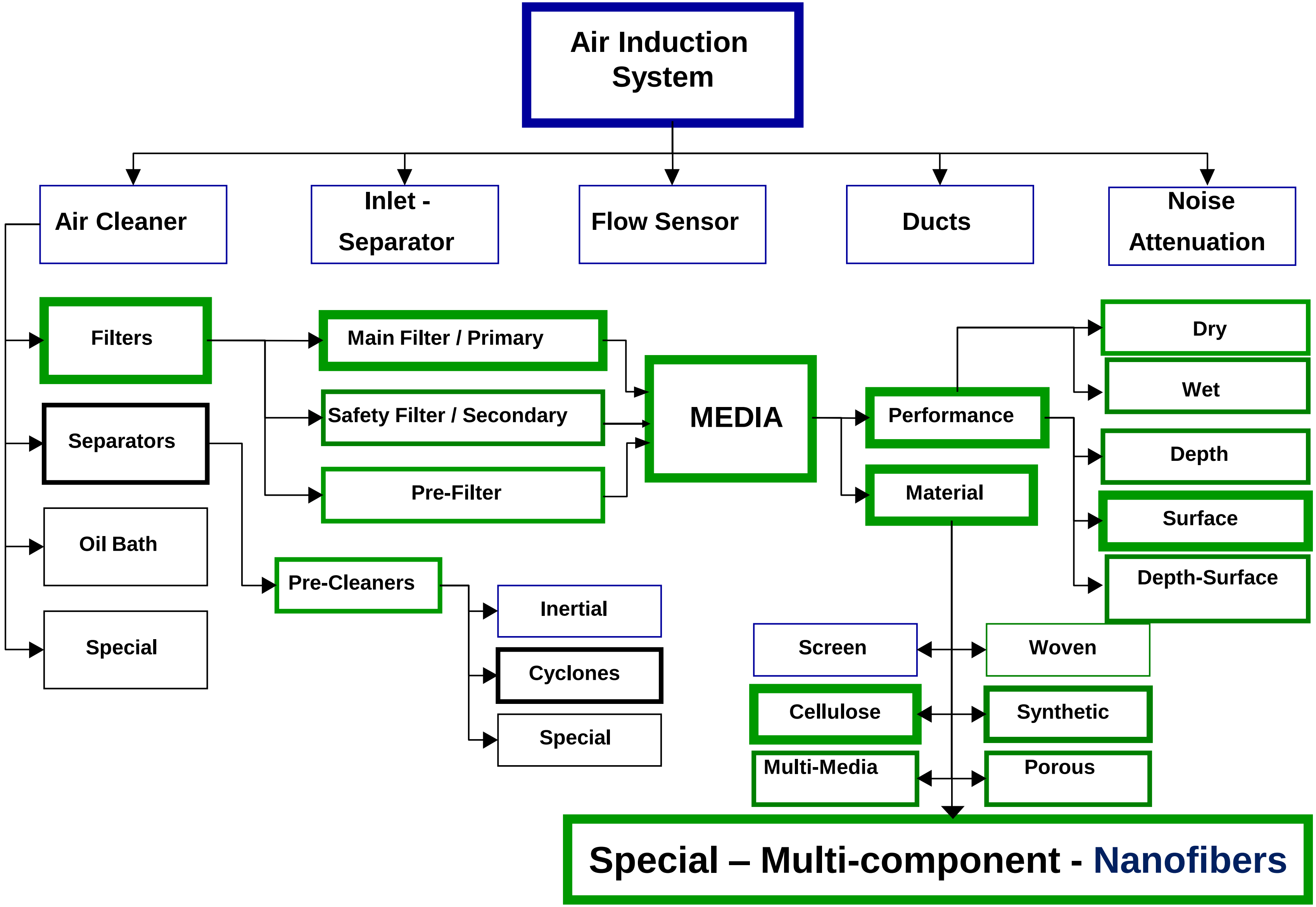


Experimental Results

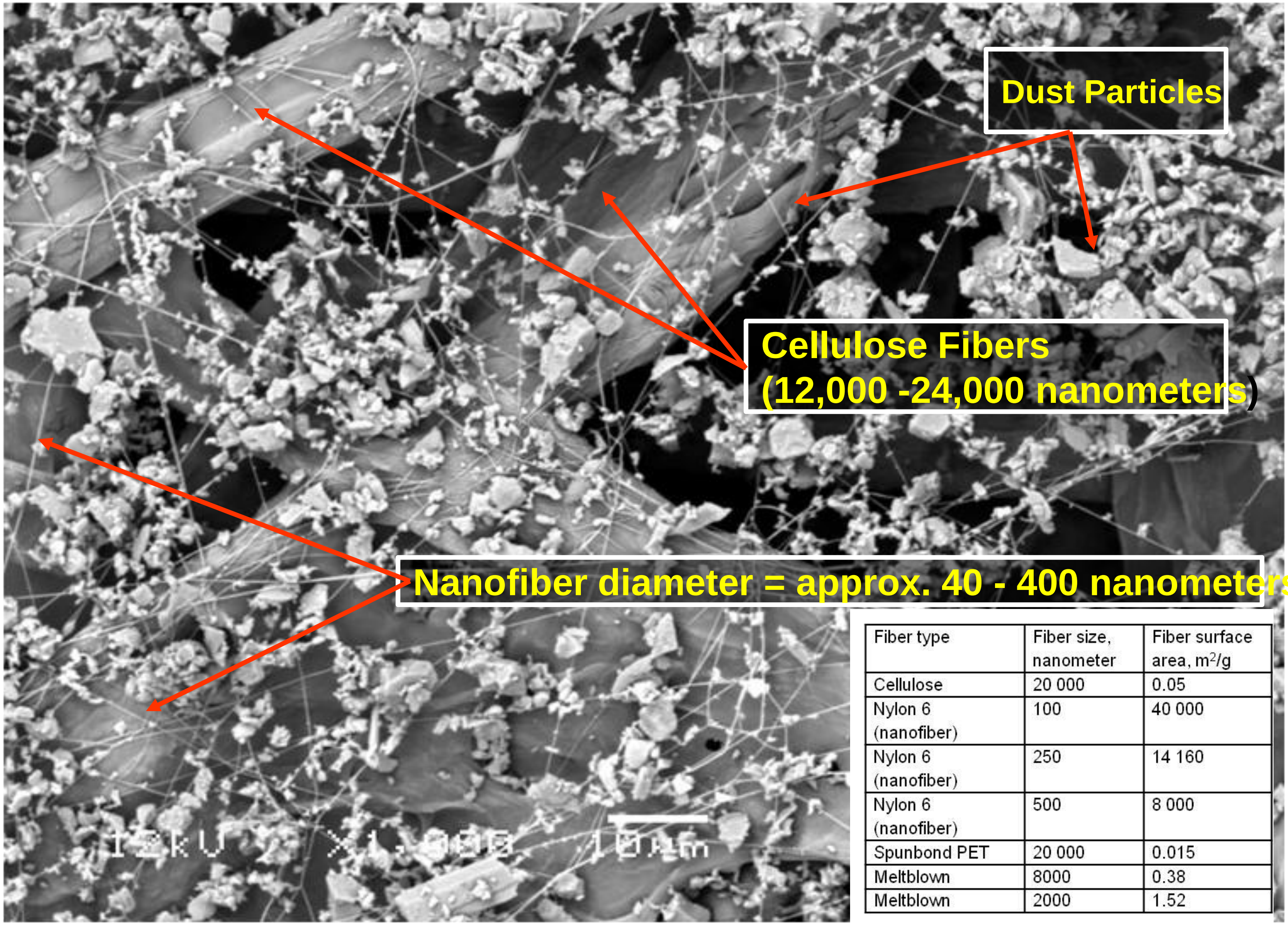
Electrostatically Charged Full Size Commercial Cabin Air Filter



Filter Media Classification



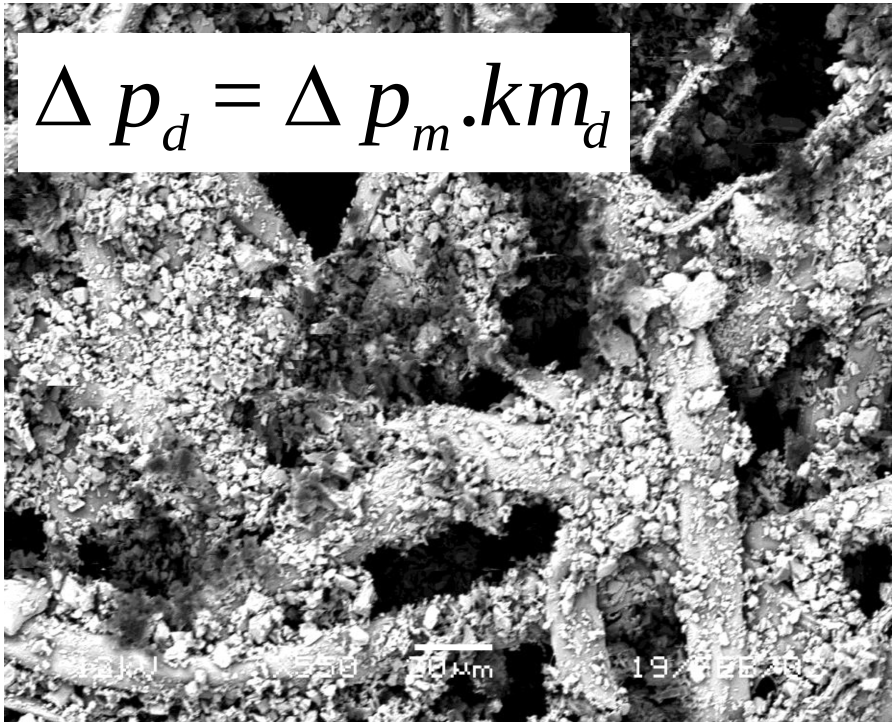
Nanofibers on Cellulose Substrate



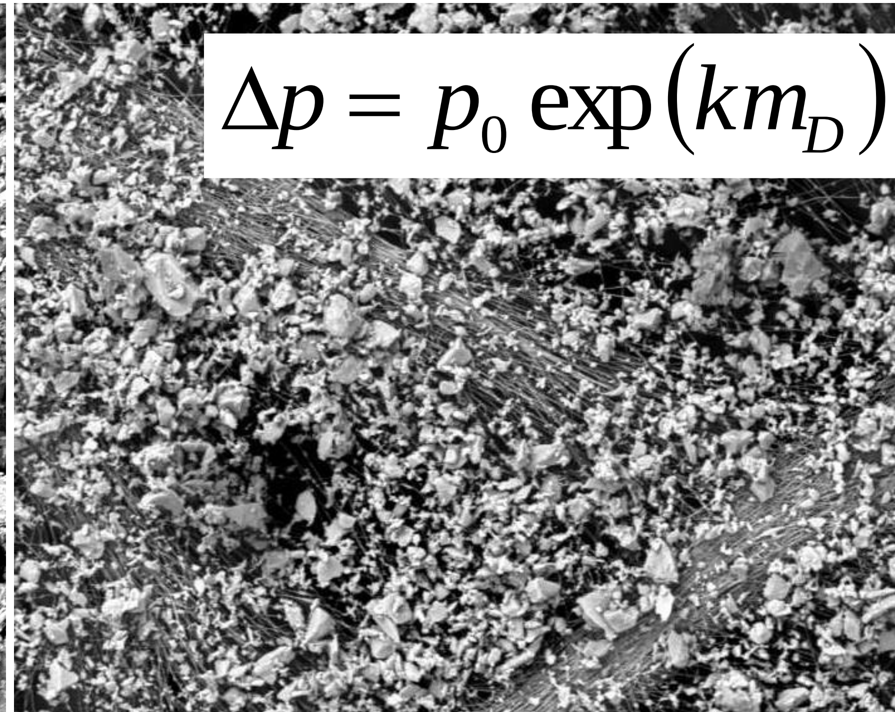
Fiber type	Fiber size, nanometer	Fiber surface area, m^2/g
Cellulose	20 000	0.05
Nylon 6 (nanofiber)	100	40 000
Nylon 6 (nanofiber)	250	14 160
Nylon 6 (nanofiber)	500	8 000
Spunbond PET	20 000	0.015
Meltblown	8000	0.38
Meltblown	2000	1.52

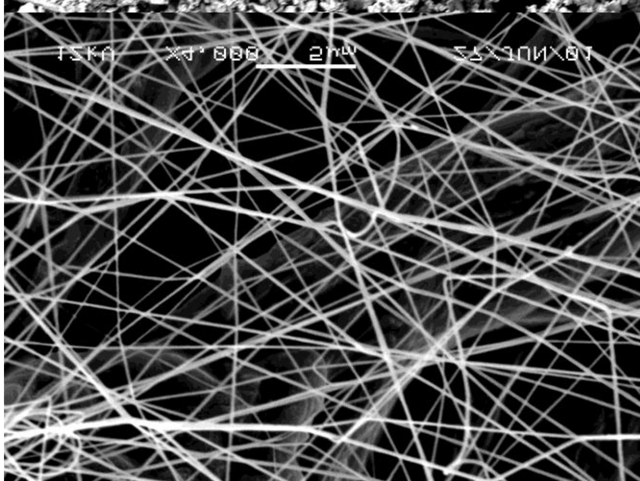
Dust Cake and Fiber Uniformity

$$\Delta p_d = \Delta p_m . k m_d$$

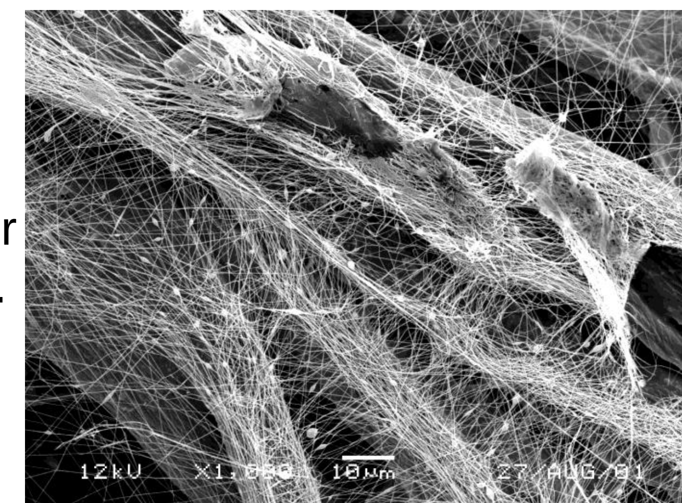


$$\Delta p = p_0 \exp\left(k m_D\right)$$





Having a top-quality Microfiber - nanofiber technology is critical.

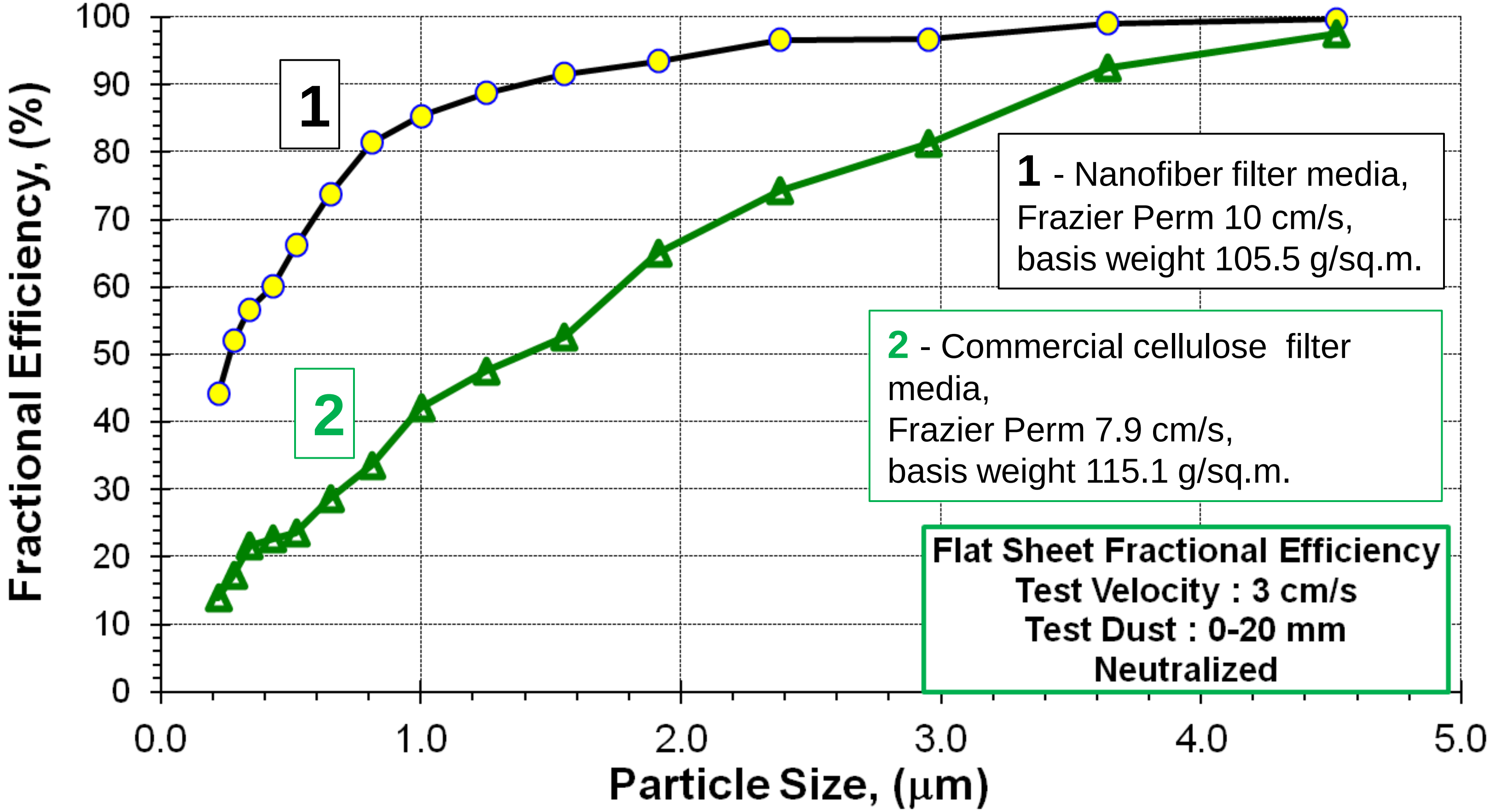


Advantage of Nanofiber Filter Media

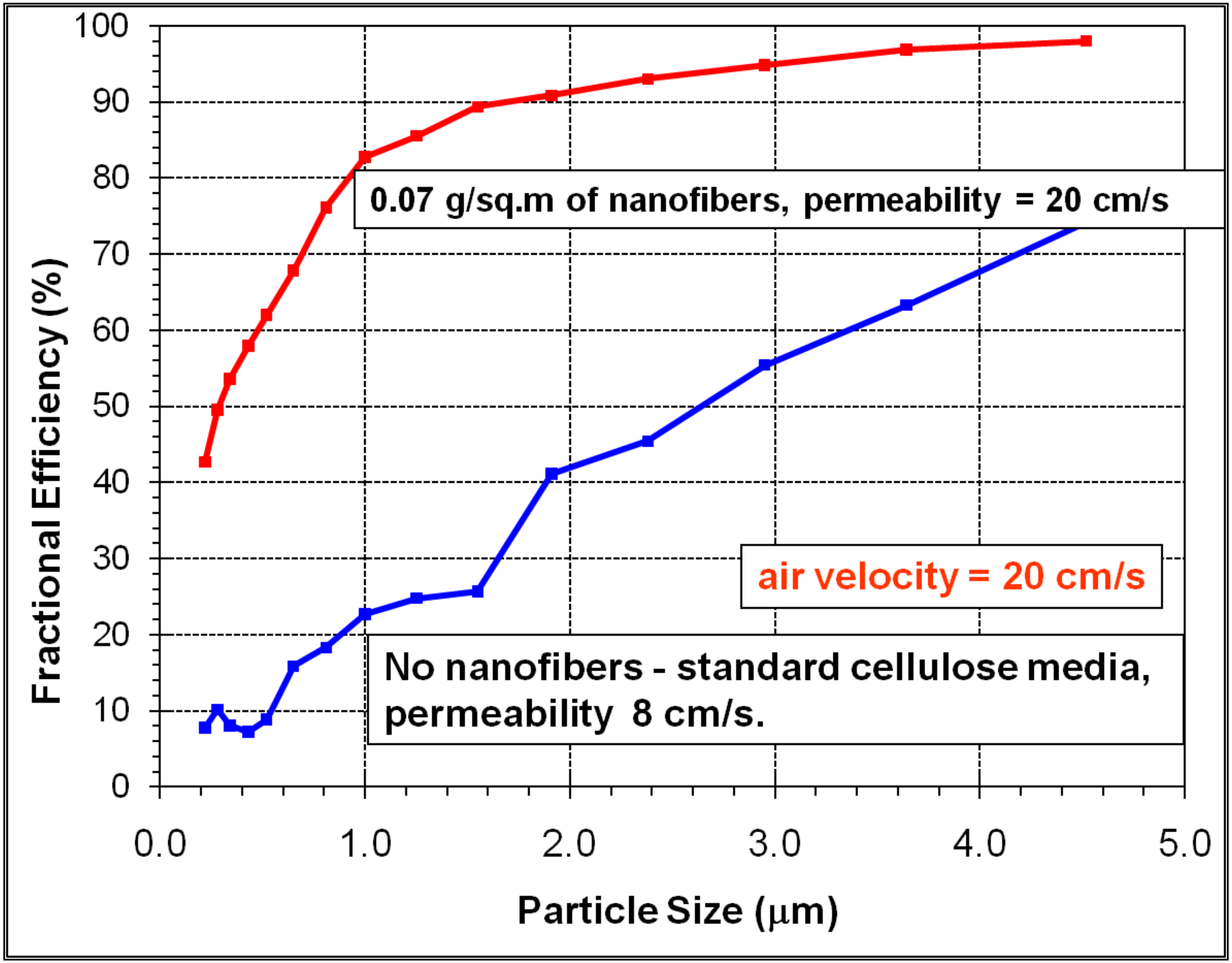
$$\Delta p = \frac{\mu \cdot v \cdot m \cdot h}{d_f^2 \cdot \rho_f \left(-0.984 \ln \beta - 0.47\right)}$$ Cellulose

$$\Delta p = 2.29 \frac{\mu \cdot v \cdot m \cdot h}{r_f \cdot \lambda}$$ Nanofiber media

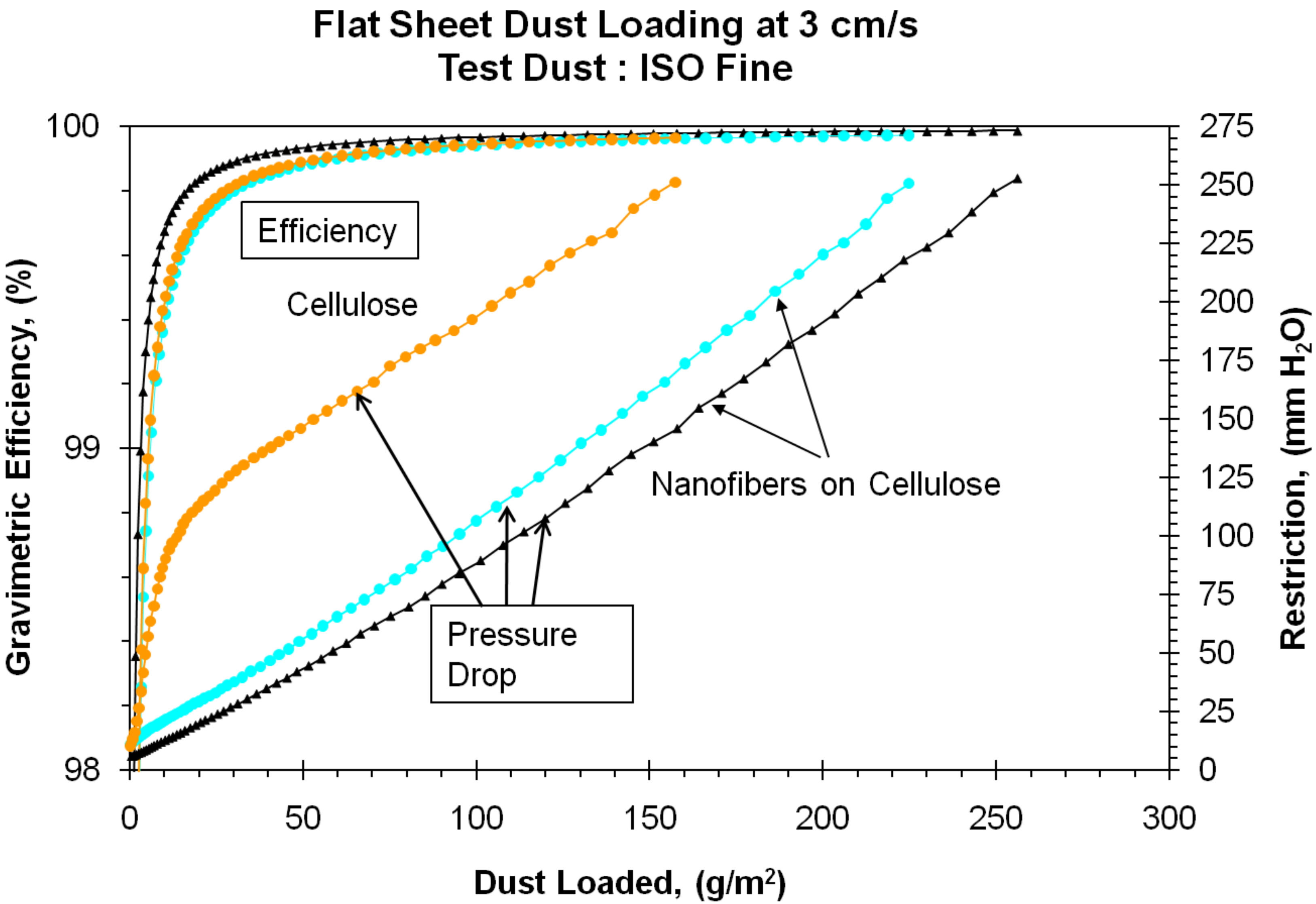
Where: µ = air dynamic viscosity, m = media basis weight, h = media thickness, ρ_f = fiber density, ß = filter solidity (or packing density): volume of fibers/volume of filter.



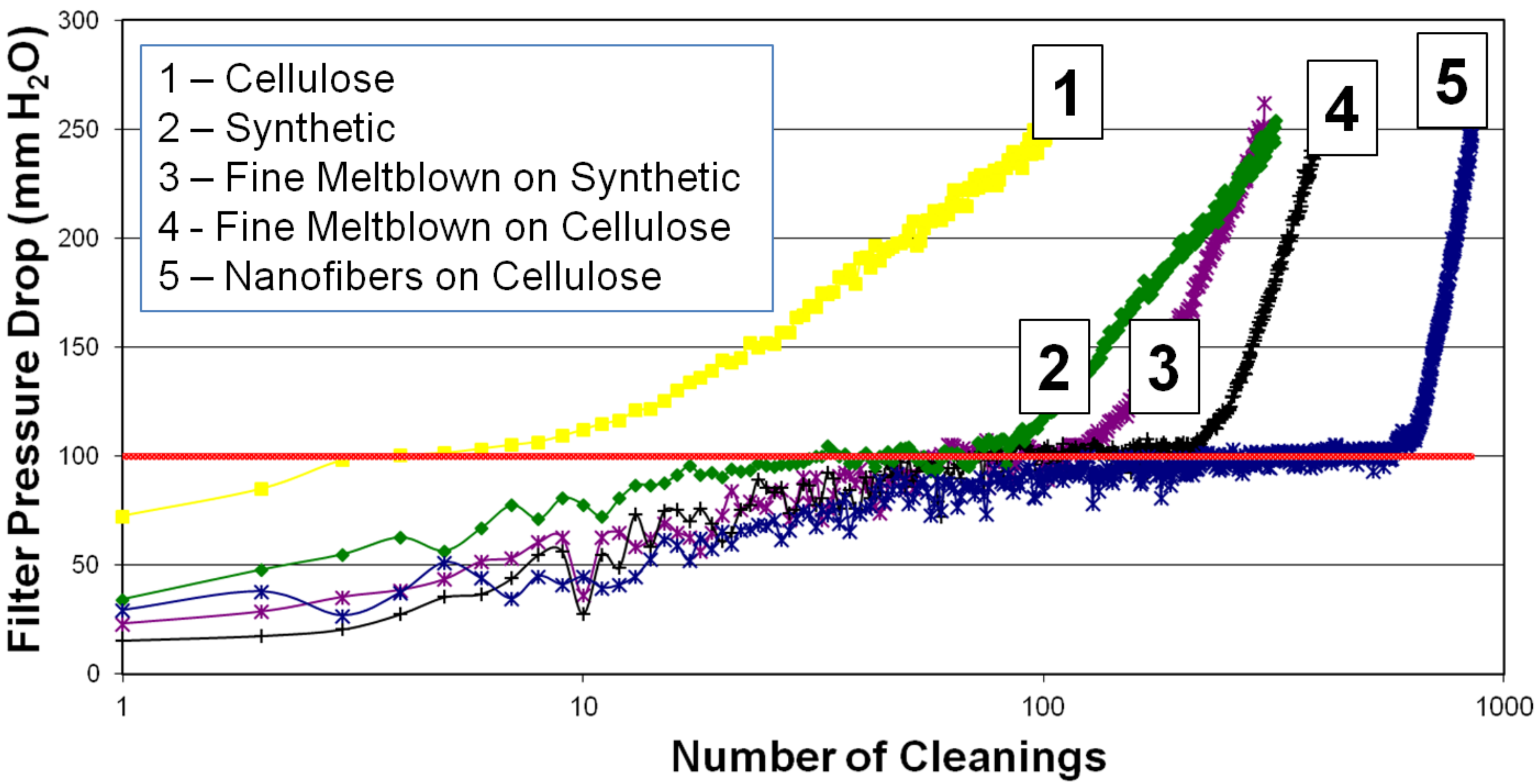
Fractional Efficiency of Nanofiber Filter Media - Cellulose Substrate



Gravimetric Performance



Self-cleaning Filtration - Gas Turbine Filters, Industrial Filters, Military Filters.



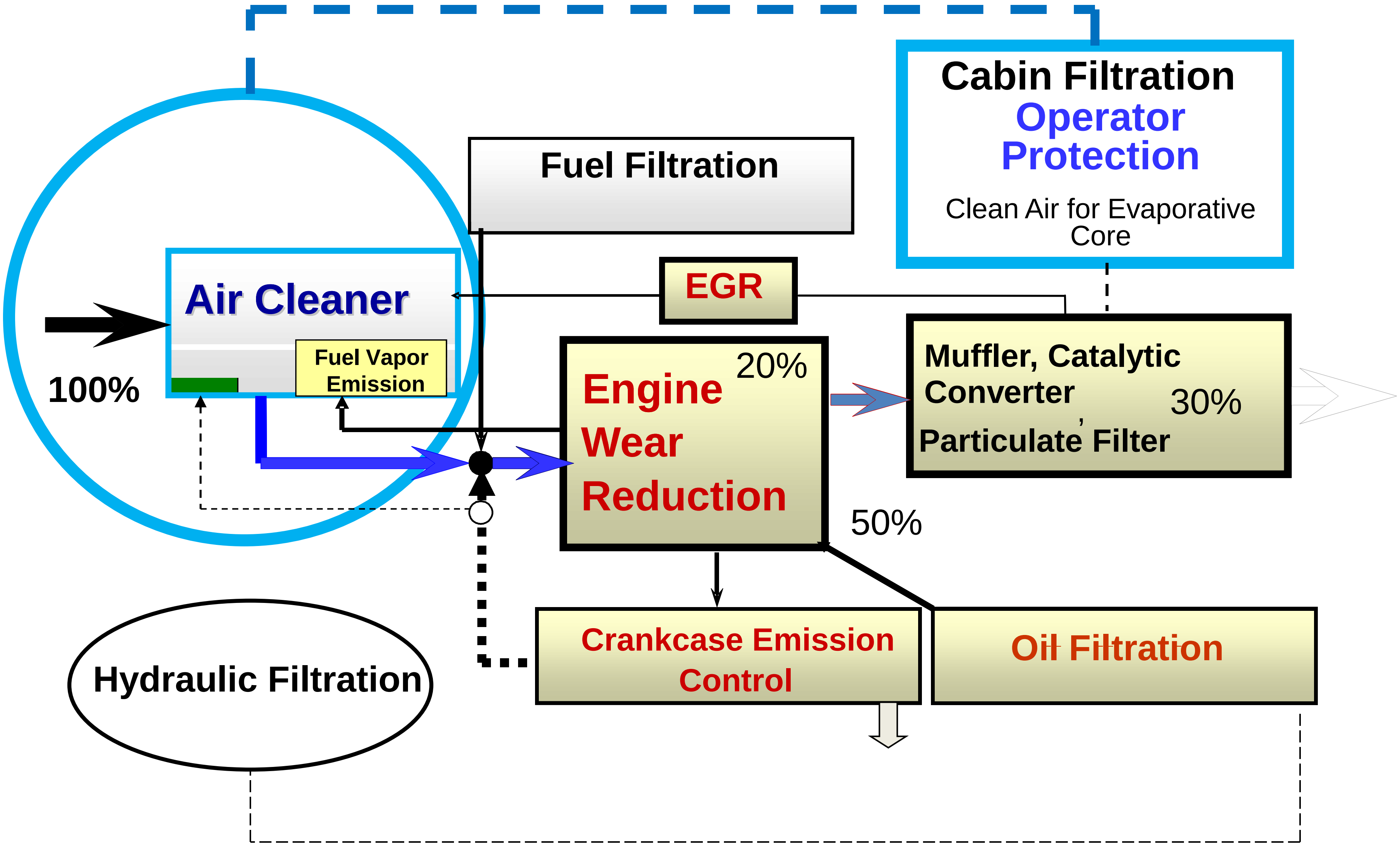
Effects of the Nanofiber Layer

- No effect on thickness of the substrate,
- Almost no increase of substrate basis weight,
- Possibility of designing high permeability (low restriction), high efficiency filter media - smaller filters or long life filters,
- Substantial improvement in initial filter efficiency ,
- Higher operational efficiency,
- Higher other performance (effect dependent on the difference of fiber diameters of the coarse media and nanofibers),
- Great iimprovement of cleanability,

APPLICATIONS

- "The **automotive sector** and is one of the positive drivers of the North American economy right now, along with **housing (HVAC**)," (Rousse, INDA 2013).
- Automotive air filtration market is worth around $3 billion (2012 USA production – 10.2 million motor vehicles)
- **HVAC** global market estimates is now worth an annual $5 billion.
- **Gas turbine air filtration -** $1.3 billion - filters and air intakes.
- **Other applications.**

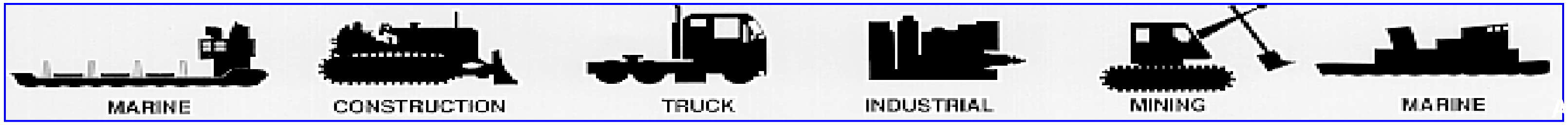
Total Motor Vehicle Filtration and Exhaust Systems



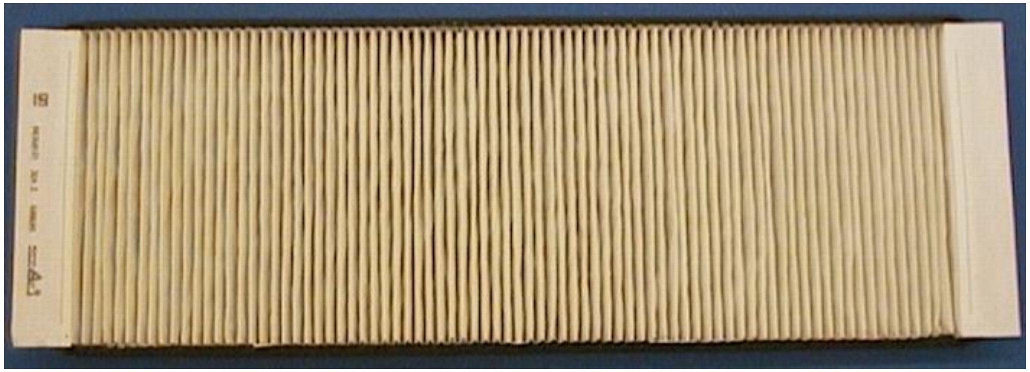
Operational Parameters

- Engine Filtration:
  - Flow rate: 5 to 5000 m^3/h (or higher)
  - Media face velocity: 1.5 to 200 cm/s (the high end of this range represents prefilters, while the range of 1.5 - 25 cm/s is common for pleated engine main filter elements).
- Automotive Cabin Filtration
  - Flow rate: 50 to 600 m^3/h
  - Media face velocity: 3 cm/s at the low blower setting (50 m^3/h) to 30 - 50 cm/s at the high blower setting (600 m^3/h) which is 6 - 25 times higher than encountered in HEPA-type filters.
- Off-Road Vehicle Cabin Filtration
  - Flow rate: 34 - 510 m^3/h in recirculating filter , 42 –127 m^3/h for the intake filter. Media face velocity: 3 – 17 cm/s.
- Crankcase ventilation
  - Flow rate: 6.5 m^3/h - 16 m^3/h, and greater.. Media face velocity: less than 50 cm/s.

Examples of Applications



Cabin Filters



Product Trends

Gas Turbine Air Filtration

General requirements:

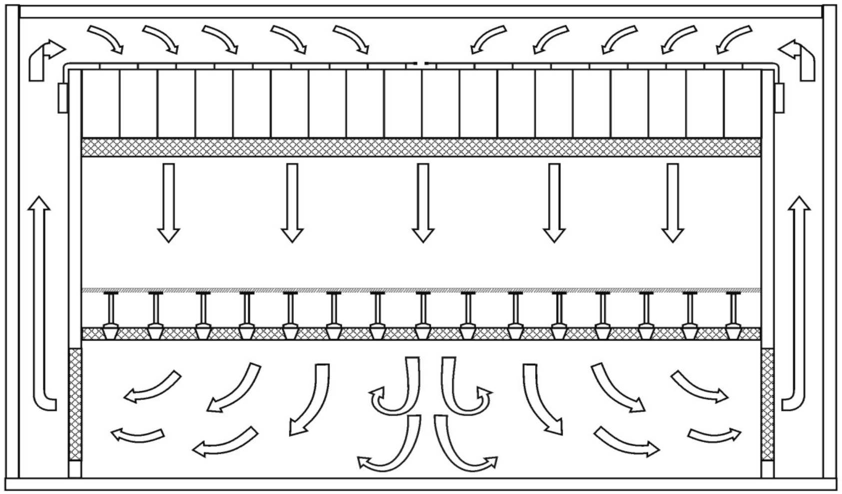
- Flow rate - 1,700 -2,500,000 m^3/h; each 100 hp requires ~ 1700 m^3/h
- Pressure drop: <500 Pa (2 inches of water)
- Loading- 500-7,000,000 t/year
- Life time: more than 2 years, 16,000 turbine fired hours

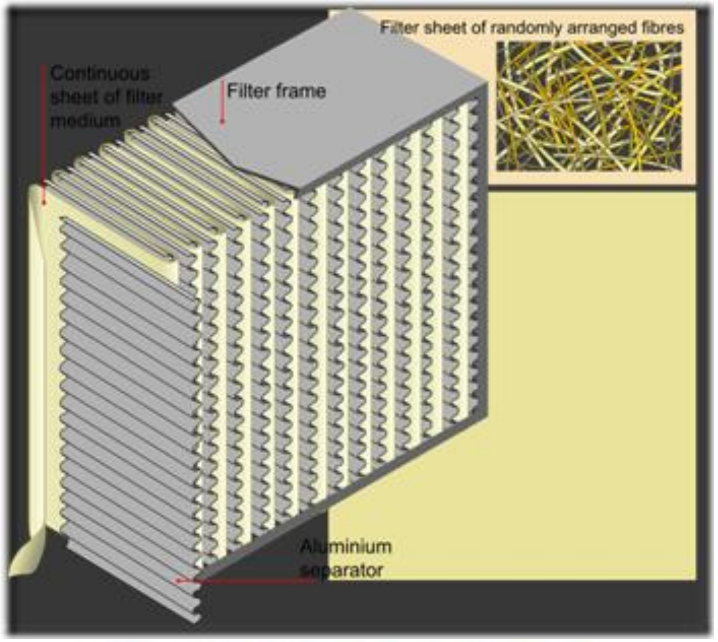
- **Minimum efficiency for ISO Fine Dust and Salt:**
  - **99.99% for 10 mm**
  - **99.95% for 5 mm**
  - **99.00% for 1 mm**
  - **DOP Efficiency - 95%**
- **Downstream dust concentration: no more than 0.067 mg/m^3**
- **Water resistance- no DP increase**

Filters for Gas Turbine and Dust Collectors

Home and Building Ventilation and Air Conditioning

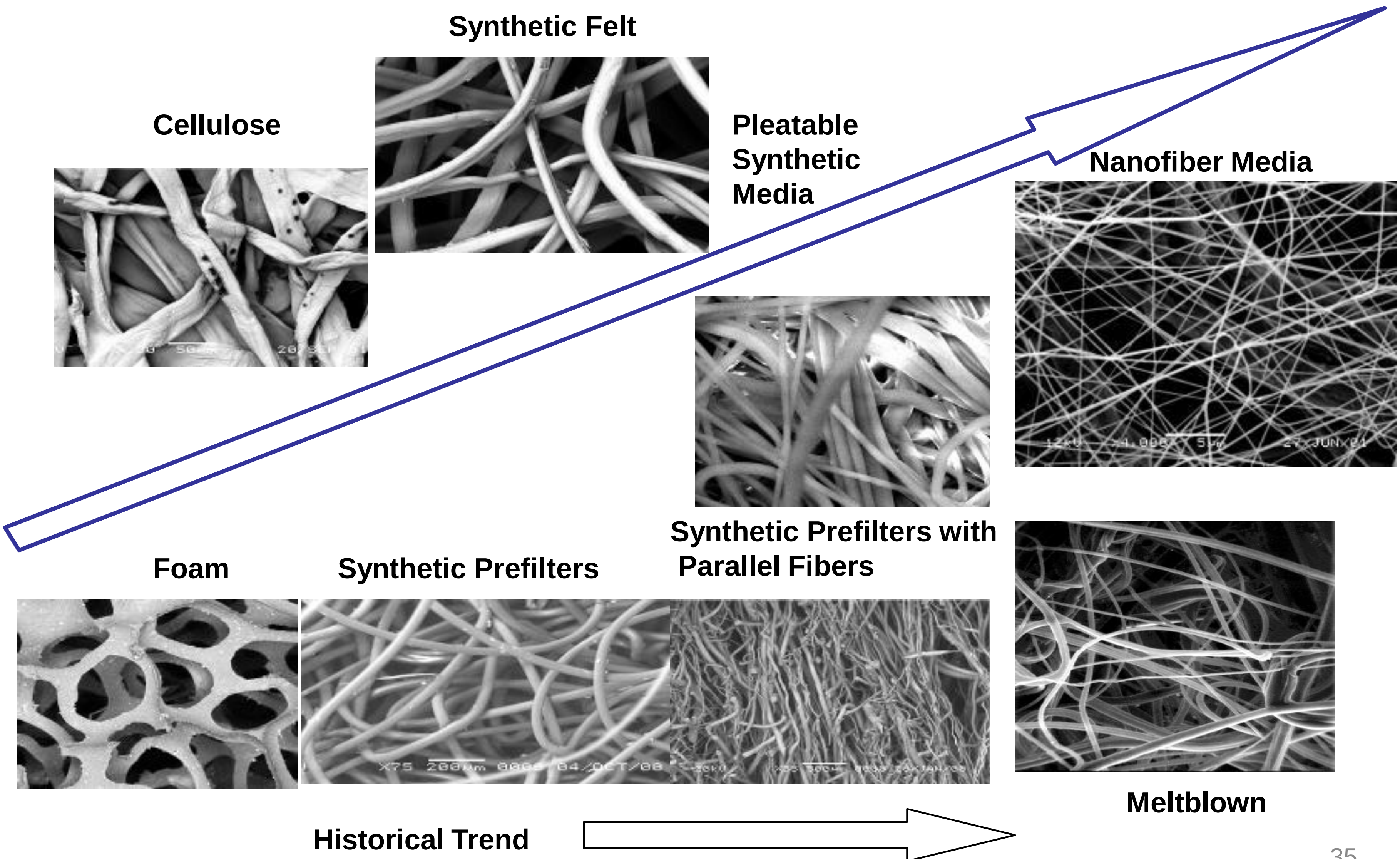
Clean Room Filtration



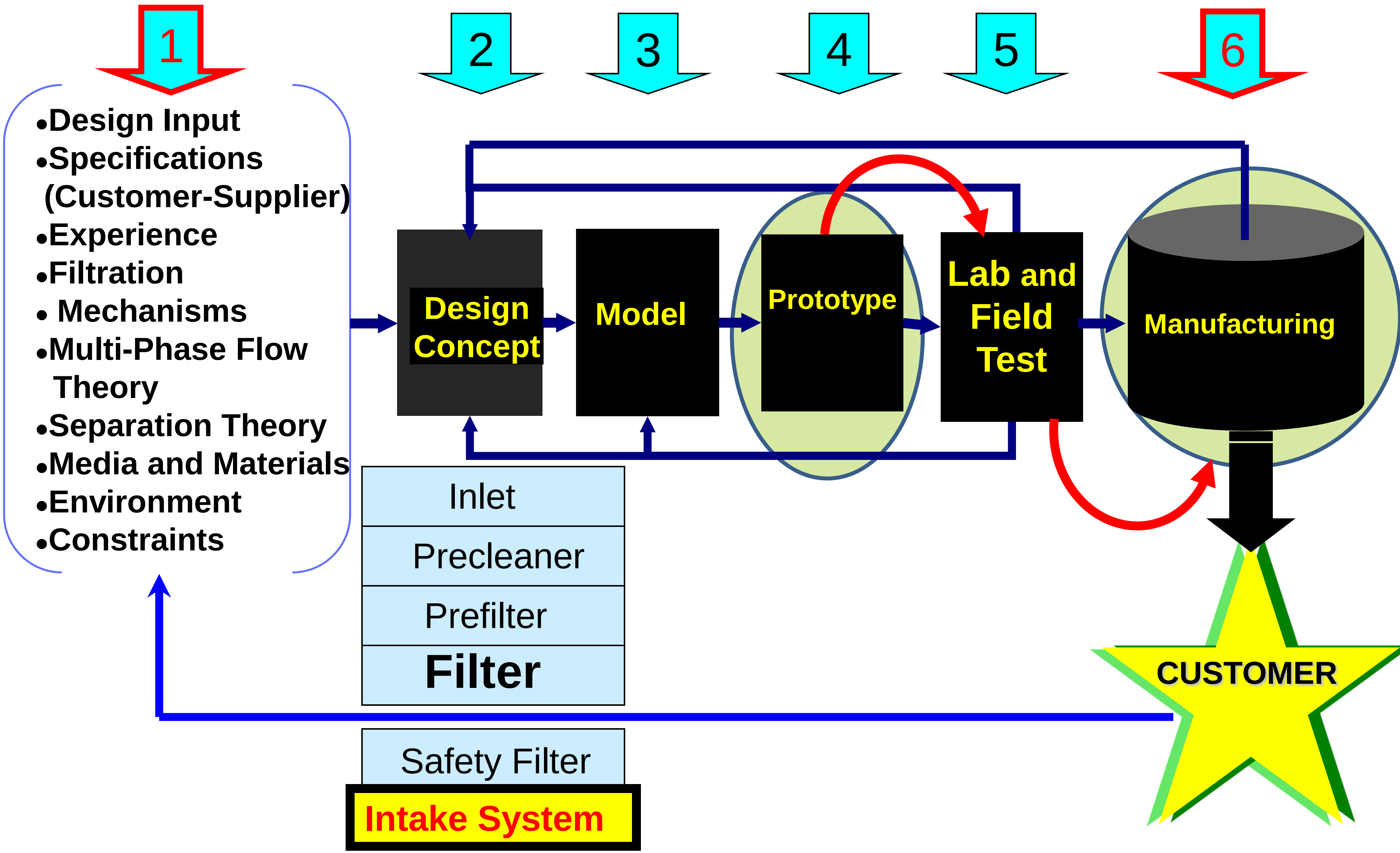


Personal Protective Equipment

Engine Air Filter Media Technology Trend



Total Filtration System Development



Conclusions

- Many air filters operate at variable flow rates and under variable environmental conditions. The wide range of field dust concentration, particle size, physical and chemical properties is an issue for theoretical study and laboratory simulation.
- Nanofiber offers high initial efficiency for small particles and fractional efficiency drastically increases when nanofibers are applied to a substrate. There is a direct correlation between filter performance and the amount of applied nanofibers.
- Initial pressure drop of nanofiber media is low, with high airflow permeability.
- Nanotechnology helps to develop smaller, more compact components/long life filters that have higher efficiency, and low initial pressure drop.
- The “positive” dust shedding - self-cleaning characteristic makes the nanofiber filters suitable for dusty environments where number of cleanings is specified.